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Injection laser threshold from the standpoint of collective resonance

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Introduction

The phenomenon of collective resonance via electromagnetic field during radiative recombination in semiconductor heterostructures provokes rising interest in recent years [1, 2]. Such many-body interactions take place in a group of dipoles having an average distance of less than the wavelength of their radiation [3]. Mutual influence of dipoles leads to their phasing and, as a result, to the formation of a "macro-dipole" with very high radiation efficiency. For the semiconductor material conditions, the superradiance (SR) pulse duration lies in sub-picosecond range. Such pulses can not be directly measured by any modern photodetector, and were discovered only using optical autocorrelation method [4].

To take into account collective resonance interaction of carriers, we must replace usual time dependence $I(t) = N/\tau e^{-t/\tau}$ by corresponding formula derived by Dicke [5] describing the time profile of the pulse.

It has been recently shown [6] that a spectrum of electroluminescence (EL) of single quantum well (QW) heterostructure at low temperatures can be very precisely described using formula for homogeneous line broadening by the superradiance effect:

$$R(\hbar\omega) = A \cdot \operatorname{sech}\left(\frac{\hbar\omega - \hbar\omega_0}{\epsilon}\right) \tag{1}$$

where characteristic energy $\epsilon = \hbar/\pi\tau_N$ (can be found from experimental spectra) i.e. the characteristic time $\tau_N = \hbar/\pi\epsilon$. These spectra must have almost exponential rise and fall. To recognize this property of a spectrum, we have to measure it very precisely and to plot spectra in semi-logarithmic scale.

In this work we would like to show how the model of collective resonance can be applied to explain the most important part of laser operation — transition from the spontaneous radiation to lasing. To do this series of spectral and temporal measurements were carried out.

1. Experimental results and discussion

The separate confinement laser double heterostructure ($\lambda = 970$ nm) based on InGaAs/GaAs single quantum well (QW) was grown by molecular beam epitaxy (MBE). EL spectra of samples were studied in wide range of temperatures from 77 K up to 300 K under the quasi-CW pump current (3 μs, 5 kHz). Some samples were prepared in special geometry: to avoid positive feedback, all edges of the sample were etched and covered by high refractive index black paint. Pump current dependence of the time coherence (τ_c) at RT have been investigated in the same manner as in [4].

EL spectra at 77 K measured through the substrate window under the different pump current are shown in semi-logarithmic scale in Fig. 1. Near the lasing threshold (which was

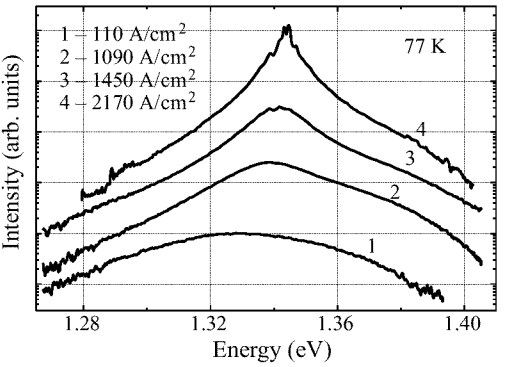

Fig. 1. Current dependence of the EL spectra measured through substrate window at low temperature (InGaAs/GaAs single QW heterostructure) plotted in semi-logarithmic scale.

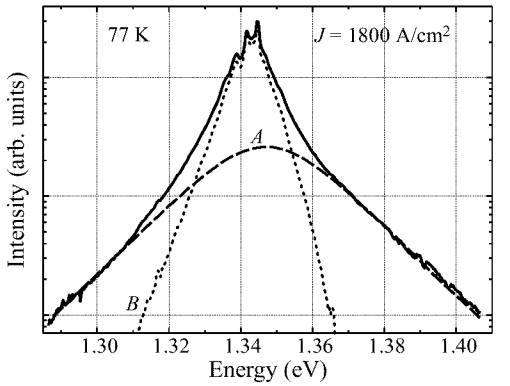

Fig. 2. EL spectrum through substrate window of InGaAs/GaAs single QW heterostructure plotted in semi-logarithmic scale. Two superradiance components of EL spectrum with different characteristic slope are shown.

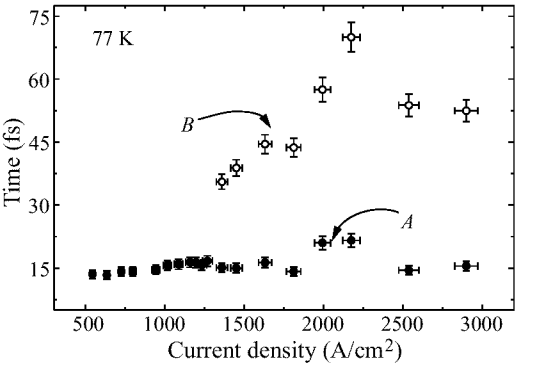

Fig. 3. Collective radiation pulse duration corresponding to components A and B as a function of pump current density.

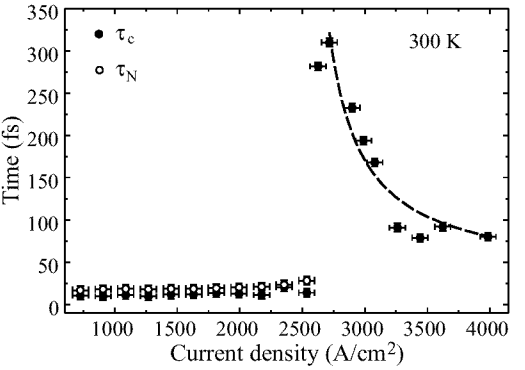

Fig. 4. FWHM of the central peak of time coherence (τ_c) at RT (solid circles) and characteristic time (τ_N) calculated from the low-energy slope of EL spectra at RT (open circles).

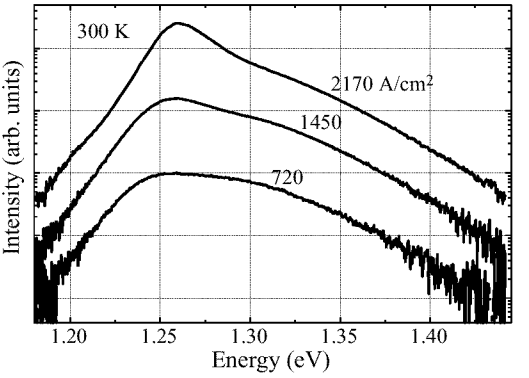

Fig. 5. Current dependence of the EL lineshape at room temperature (InGaAs/GaAs single QW heterostructure) plotted in semi-logarithmic scale.

approximately 1400 A/cm^2) EL spectrum has a complex shape that can be presented as a superposition of two superradiance components with different characteristic slope (Fig. 2).

Our estimate of the corresponding duration of components A and B coming from Eq. (1) is plotted as a function of the pump current in Fig. 3. Characteristic time of the component A is practically constant in wide range of pump current. We suppose that component A describes the superradiance in semiconductor without feedback. Component B corresponds to that part of superradiance pulse, which is changed by the laser cavity. Due to rather narrow gain spectrum amplified SR pulse becomes longer up to 70 fs (Fig. 3). Intensity of A component is so small in comparison with B one that it practically could not be detected using time-resolving investigations.

Full width at half-maximum level (FWHM) of the central peak of time coherence, which should corresponds to superradiance characteristic time, is shown in Fig. 4. Below the lasing threshold this results were compared with the characteristic time (τ_N) which was calculated from the low-energy slope of EL spectra at RT (Fig. 5) and also shown in Fig. 4. According to our experiments τ_c approximately in 2 times lower than τ_N. This difference can be caused by the significant inhomogeneous line broadening. As a result the duration of the single superradiance pulse is longer than one estimated from time coherence pattern.

It should be noticed that both τ_N and τ_c practically do not depend on the pump current below the threshold, which is in a good agreement with our previous results [6].

At room temperature inhomogeneous line broadening does not allow to distinguish components of luminescence spectra mentioned above. However, narrow and more intensive component B is clearly presented in time coherence pattern above the threshold. It is important that at RT the characteristic time of SR component B is longer than one at 77 K.

2. Conclusions

Mechanism of laser threshold is considered in terms of superradiance. Presence of short coherent pulses has been demonstrated below, at and above laser threshold in wide temperature range. Existence of positive feedback leads to SR pulse becomes longer. Luminescence lineshape above threshold has a complex structure but is well described using the theory of collective recombination. Spectral investigations at low and room temperature, as well as time coherence measurements at RT allow estimating the characteristic time of superradiance pulse in these two modes. The maximum duration of the pulse has been found as low as 300 fs at RT and 70 fs at 77 K.

Acknowledgements

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